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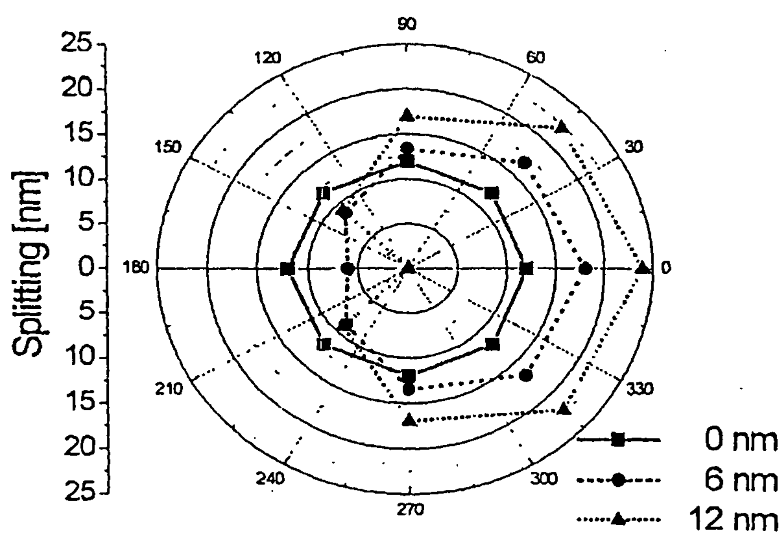


(57) Abstract

The present invention relates to an optical based bending sensor. In particular, the present invention relates to a fibre-based bending sensor for the determination of the direction and the amplitude of a bend. The present invention further relates to fibre-based bending sensors using long-period fibre gratings (LPG), in which the intrinsic properties of the fibre and the bend sensitivity of LPG is utilised. In a preferred embodiment, the connection between the Core Concentricity Error (CCE) of the fibre and the LPG in the asymmetric bend behaviour results in coupling resonance between the core and the cladding modes. Thereby a relative splitting of transmission peaks in the spectrum of the LPG is induced, which is used to determine the bending amplitude and direction.

A SENSOR AND A METHOD FOR DETERMINING THE DIRECTION AND THE AMPLITUDE OF A BEND

The present invention relates to an optical based bending sensor. In particular, the present invention relates to a fibre-based bending sensor for the determination of the direction and the amplitude of a bend. The present invention further relates to fibre-based bending sensors using long-period fibre gratings.

Interest in Long-Period Fibre Gratings (LPG) is increasing both in optical communication, where they are used for gain flattening and as sensor elements to measure strain, temperature, and refractive index. LPG's are also under consideration as bending sensors to monitor structural changes. Patrick et. al. (H.J. Patrick, C.C. Chang, S.T. Vohra, Elect. Lett. 34 (1998) 1775) observed a bend direction asymmetry for the centre-wavelength position of one LPG core-cladding mode resonance. This effect has been used to construct a bend sensor that measures both direction and amplitude of a bend using two LPG's oriented with opposite bend direction sensitivity.

As previously mentioned, H. Patrick et al. discloses that bending of a waveguide induces an absolute shift in the transmission spectrum. This wavelength shift is larger for bending in one direction compared to bending in the opposite direction.

It is a disadvantage that in order to obtain a directional bending sensor two LPG's oriented in opposite orientation are required.

It is a further disadvantage that the observed effect is a combined effect involving both bending and strain.

It is a further disadvantage that in the case where the combined effect of bend and strain gives a possibility to detect the bend direction and amplitude, one of the directions is very poorly determined.

It is a still further disadvantage that only the shift in absolute resonance frequency is utilised for obtaining information regarding the bending of the fibre.

It is a still further disadvantage that the sensor configurations suggested by H. Patrick et al. are sensitive to temperature, strain, and refractive index induced drift.

It is a still further disadvantage that the sensor configuration suggested by H. Patrick et. al. does not give a linear wavelength shift for small curvatures, wherefore the sensor has a reduced resolution for small curvatures.

US 5,641,956 discloses the concept of using LPG's in sensors for the determination of a variety of physical parameters using a transmission spectrum. Also the concept of using LPG's for the determination of the amplitude of a bend is mentioned.

It is a disadvantage that the sensor configurations suggested in US 5,641,956 are sensitive to temperature, strain, and refractive index induced drift.

It is a further disadvantage that no direct information regarding the direction of a bend is obtained. For direction sensitivity strain is needed.

It is an object of the present invention to provide a sensor sensitive to both the direction and the amplitude of a bend.

It is a further object of the present invention to provide a sensor for determining both the direction and the amplitude of a bend using a fibre-based sensor.

It is a still further object of the present invention to provide a bending sensor where problems due to temperature drift is essentially avoided.

It is a still further object of the present invention to provide a bending sensor that has a linear respond for small curvatures.

It is a still further object of the present invention to provide a bending sensor that can be placed at a strain free position as to durability of the sensor.

It is a still further object of the present invention to provide a bending sensor which is not sensitive to strain so that the bending sensitive element can be placed at any position of the object investigated regardless of the strain at that position.

It is a still further object of the present invention to provide a method for determining the direction and the amplitude of a bending.

It is a still further object of the present invention to provide a method for determining both the direction and the amplitude of a bending using a fibre-based sensor.

The above-mentioned objects are complied by providing in a first aspect of the present invention, a direction sensitive bending sensor comprising:

- an optical waveguide structure having a first centre axis extending in a longitudinal direction of the optical waveguide structure, said optical waveguide structure comprising, in a cross-section perpendicular to the longitudinal direction, a core and a cladding region,

    - the core region having a second centre axis extending in the longitudinal direction of the optical waveguide, said second centre axis being different from the first centre axis, or

    - the cladding region having a second centre axis extending in the longitudinal direction of the optical waveguide, said second centre axis being different from the first centre axis,

- means for providing light into the core region of the optical waveguide structure,

- a grating structure introduced into the optical waveguide structure so as to couple part of a guided mode in the core region to a mode in the cladding region, and

- means for determining a parameter associated with a coupling resonance between the core and the cladding modes by detecting light transmitted by the optical waveguide structure, said parameter relating to an amplitude and a direction of a bend.

In a second aspect the present invention relates to a method for determining the amplitude and the direction of a bend, said method comprising the steps of:

- providing an optical waveguide structure having a first centre axis extending in a longitudinal direction of the optical waveguide structure, said optical waveguide structure comprising, in a cross-section perpendicular to the longitudinal direction, a core and a cladding region,

  - the core region having a second centre axis extending in the longitudinal direction of the optical waveguide, said second centre axis being different from the first centre axis, or

  - the cladding region having a second centre axis extending in the longitudinal direction of the optical waveguide, said second centre axis being different from the first centre axis,

- providing light into the core region of the optical waveguide structure,

- introducing into the optical waveguide structure an optical grating structure so as to couple part of guided mode in the core region to modes in the cladding region, and

- determining a parameter associated with a coupling resonance between the core and the cladding modes by detecting light transmitted by the optical waveguide structure, said parameter relating to the amplitude and the direction of the bend.

The first centre axis of the waveguide structure is preferably the geometrical centre of the waveguide. The second centre axis of the core or cladding region is preferably the geometrical centre of the core or cladding region.

By core region is meant any region capable of guiding electromagnetic radiation inside the waveguide structure. The core region may be defined during manufacture of the waveguide structure as an area having a refractive index being higher than the refractive index of a surrounding cladding region. Alternatively, the core region may be defined or redefined after the manufacture of the waveguide structure. This may be provided by exposing the waveguide to e.g. ultra-violet (UV) radiation or by introducing an additional material into the waveguide.

The cladding region may comprise an inner and an outer cladding where the refractive index of the inner cladding is larger than the refractive index of the outer cladding. Preferably, the outer cladding is surrounded by an absorbing layer for absorbing any modes in the outer cladding and thereby prevent coupling to cladding modes in the outer cladding. Thus the coupling resonances only occur between a core mode and the inner cladding mode. This has the advantage that the surrounding medium does not perturb the core/inner cladding mode resonances, which is very undesirable especially in the case of an absorbing surrounding. Another advantage is that the number of cladding modes can be reduced thus increasing the spacing in wavelength between the different resonance's and thereby allowing for more LPG's in the same fibre.

The first axis of the waveguide structure may be shifted from the geometrical centre if geometrical or refractive index asymmetries are present in the core or cladding. These asymmetries may be defined during or after manufacture. The asymmetry of a given waveguide structure may be marked visually on the outer surface of the waveguide structure by e.g. a colour indicator.

The determined parameter may relate to a splitting of a resonance coupling in a transmission spectrum when light propagates along the longitudinal direction of the optical waveguide structure. The waveguide structure may be an optical fibre.

The grating structure introduced into the waveguide may comprise a long-period grating typically having a period, Λ, within the range 10–5000 μm, preferably in the range 50-1000 μm and even more preferably in the range 100-600 μm.

The means for providing light into the core may be a laser emitting light at essentially a single wavelength, such as a semiconductor, fibre lasers or gas laser. The sensor may further comprise control means for varying the emitted wavelength so that a scanning over a predetermined wavelength range with a predetermined resolution may be provided. The determining means typically comprises a photosensitive detector capable of detecting the transmitted light.

Alternatively the means for providing light into the core region may comprise a laser emitting light at a plurality of wavelengths or a broadband source, e.g. LED. In this situation the determining means may comprise an optical spectrum analyser for determining a transmission spectrum of the optical waveguide structure.

The optical waveguide structure may further comprise means for reflecting light transmitted by the grating structure so as to reflect light back into the waveguide structure. In this way, the sensor is capable of operating in a reflection mode configuration.

In a third aspect the present invention relates to a method for determining an amplitude and a direction of a bend in a plane, said method comprising the steps of:

- providing an optical waveguide structure having a first and a second end and having a first centre axis extending in a longitudinal direction of the optical waveguide structure, said optical waveguide structure comprising, in a cross-section perpendicular to the longitudinal direction, a core and a cladding region,

    - the core region having a second centre axis extending in the longitudinal direction of the optical waveguide structure, said second centre axis being different from the first centre axis, or

- the cladding region having a second centre axis extending in the longitudinal direction of the optical waveguide structure, said second centre axis being different from the first centre axis, and

- providing light into the core region of the optical waveguide structure,

- bending the optical waveguide structure in the plane and determining a value being associated with a splitted coupling resonance between the core region and the cladding region, said determined value being uniquely associated with the amplitude and the direction of the bend.

The deviation between the first and second centre axis, in the cross-section, defines an asymmetry axis. Preferably, the asymmetry axis is essentially perpendicular to the plane.

In a fourth aspect the present invention relates to a method for determining an amplitude and a direction of a bend, said method comprising the steps of:

- providing a first and a second optical waveguide structure each having a first and a second end and having a first centre axis extending in a longitudinal direction of the optical waveguide structure, each optical waveguide structure comprising, in a cross-section perpendicular to the longitudinal direction, a core and a cladding region,

- the core region having a second centre axis extending in the longitudinal direction of the optical waveguide structure, said second centre axis being different from the first centre axis, or

- the cladding region having a second centre axis extending in the longitudinal direction of the optical waveguide structure, said second centre axis being different from the first centre axis,

wherein the deviation between the first and second centre axis, in the cross-sections, defines a first and a second asymmetry axis for the first

and second waveguide structures, respectively, the first asymmetry axis being different from the second asymmetry axis,

- providing light into the core region of the optical waveguide structure,

- bending the first and second optical waveguide structure in the same direction and determining a first and second value being associated with a first and second splitted coupling resonance between the core and cladding region of the first and second waveguide structures, respectively, said determined first and second values being uniquely associated with the amplitude and the direction of the bend.

Preferably, the first asymmetry axis is essentially perpendicular to the second asymmetry axis.

Other objects and features of the invention will become apparent from the following specification which refers to the accompanying figures in which:

Figure 1 is a graph showing the transmission for a fibre with three different curvatures. It is seen that the change in splitting is increasing for positive curvatures 0° and decreasing for negative curvatures 180°.

Figure 2 shows the bend characterisation set-up. By depressing the ruler at the centre a bend is induced in the fibre. The bend direction is determined by the sticker angle, θ. The mass m gives a constant force in the fibre.

Figure 3 is a graph showing the splitting of transmission peaks for different curvatures, plotted in the upwards-downwards bending plane.

Figure 4 is a graph showing the transmission spectra. a) Fibre A, b) Fibre B. The labelling shows the cladding mode (lυ) to which the coupling from the core mode occur.

Figure 5 a) and b) shows polar plots of resonance splitting for coupling to the (17)-cladding mode for fibre A and fibre B respectively. The angle from the sticker is the angular co-ordinate and the splitting is the radial co-ordinate. Points with the same curvature are connected.

Figure 6 is an illustration of the addition of the contribution to the resonance splitting from core concentricity error and from the bending of the fibre.

Figure 7 shows a polar plot of resonance splitting similar to Figure 5.

In the present specification the influence of some intrinsic properties of the fibre upon the bend sensitivity of LPG's is investigated. In particular, the specification describes a preferred embodiment wherein the connection between a Core Concentricity Error (CCE) of the fibre and the LPG results in coupling resonances between the core and the cladding modes. Finally, a qualitative explanation of the phenomenon is given in the form of experimental results.

The Core Concentricity Error is a measure of the lack of concentricity of an optical waveguide and either the core or the cladding of the waveguide. The CCE of a waveguide is measured in the displacement in μm of the centre axis of the waveguide and the centre axis of the core or the cladding of the waveguide. As mentioned above, such intrinsic misalignment results in coupling resonances between the core and the cladding modes in the waveguide structure. Preferably, the waveguide structure is an optical fibre, but can also be planar waveguide structures such as planar silica waveguides typically used in Silicon wafer technology.

The LPG introduces one or more resonance peaks in the transmission spectrum of the fibre, and the coupling resonances resulting from the CCE can split such peaks into two wavelength-separated peaks due to coupling resonance between the core and the cladding modes. This splitting is attributed to a breaking of symmetry. A pair of splitted peaks is shown in Figure 1. Here the transmission spectrum is shown when the fibre is straight, bent upwards or bent downwards, respectively. It is seen that the wavelength-separation of the splitted peaks is increased for a downward bend

and decreased for an upward bend. Thereby amplitude and direction of the bend are detected. Temperature and strain do not influence the magnitude of the splitting.

As the distance of two coupling resonances is determined instead of determining the absolute wavelengths of the coupling resonances, the sensor according to the present invention is essentially insensitive to temperature changes. In a standard Bragg grating based sensor the absolute shift in Bragg wavelength is either due to a strain or temperature change without a possibility of distinguishing between the two. In the sensor according to the present invention, the strain is known from the distance in wavelength of two coupling resonances, and the absolute wavelength change which is due to a combination of bent/strain and temperature change can be determined. Knowing the strain and the absolute value of the Bragg wavelength the temperature can be determined with high precision. Thus, the sensor according to present invention measures simultaneously and independently temperature and bent/strain with only one waveguide structure involved.

Two step index fibres with comparable index profile are investigated. Fibre A has a standard CCE of 0.1 μm whereas fibre B has a CCE of 2.4 μm. The parameters are summarised in Table 1, where ρ is the fibre core radius and Δn the index step.

Table 1.

	ρ	Δn	CCE
Fibre A	2.25 μm	0.017	0.1 μm
Fibre B	2.55 μm	0.015	2.4 μm

A 3 cm long LPG was inscribed in each of the unloaded fibres by exposing them to 248 nm excimer laser light through an amplitude mask with a period of $\Lambda = 250$ μm. A fluence of approximately 5000 J/cm^2 in 20000 pulses was applied. Prior to the inscription tape stickers 6 were placed on the untwisted fibre in order to be able to control the rotation of the fibre around its own longitudinal axis.

Bending of the fibre 1 was induced by a metal ruler 4 with a fibre groove in a three-point bend set-up, as shown in Figure 2. The angle of the tape sticker 6 relative to the vertical plane is denoted θ. Depressing the centre with the tip of a rod performs

deformation of the metal ruler 4. The curvature is calculated from the depression using standard formulas. Since this is a three-point bend the curvature varies between the two end points and it is therefore important to place the LPG 2 as symmetric around the depression point as possible to get the most symmetric and homogeneous bend over the LPG 2. With a 0.5 cm misalignment of the LPG 2 from the centre of the metal ruler, the variation of bend curvature along the 3 cm long LPG is 9 %. Even though this is a relatively large deviation it is not critical for the results since the variation is the same for all bend curvatures.

To ensure that changes in the transmission spectrum are due to bending and do not originate from changes in strain along the fibre a constant force is applied to the fibre in longitudinal direction by a weight 8 as illustrated in Figure 2. The tape sticker 6 is again used to determine the orientation of the fibre 1.

Possible detection systems consists of:

a) A tuneable light source (or a broadband source in combination with a tuneable notch filter) with a tuning range exceeding the maximum resonance splitting.
b) A photodiode.
c) Electronics, in particular a simple digital signal processing unit (chip).

A narrow light source is scanned in wavelength with a certain scan velocity, e.g. by varying a control parameter such as temperature or injection current. When scanning over a splitted resonance the signal from the photodiode versus scanning parameter will show two dips, corresponding to the two dips in the transmission spectrum of the splitted resonance shown in Figure 1.

The detection of the splitting can be performed by a simple and cheap digital signal-processing unit. Since the splitting is only dependent on the bend magnitude and direction the magnitude of the splitting in any unit determines the bend. This particularly eliminates the need to know the absolute wavelength, temperature or strain and especially, no spectrum analyser is needed.

The same detection principle will work using a broader light source, e.g. a light emitting diode (LED), showing some (stable) etalon effect. A broader light source may also be used in a heterodyne or homodyne detection scheme including e.g. an unbalanced interferometer.

The splitting of transmission peaks for different curvatures for $\theta = 0°$ and $\theta = 180°$ axis is plotted in the graph shown in Figure 3. Positive curvature is along $\theta = 0°$ and negative along $\theta = 180°$. A linear relation of splitting vs. curvature is clearly observed even at small curvatures. Here it can be seen that it is possible to detect both amplitude and direction of the bend.

In Figure 4a and 4b, the transmission spectra for straight LPG's in fibre A and B are shown. The dips correspond to coupling of the core mode to 4 or 5 cladding modes respectively. We have labelled the cladding modes based on the work by Erdogan (T. Erdogan, J. Opt. Am. 14 (1997) 1760.). No splitting of the coupling resonances is seen for fibre A (without CCE), whereas for fibre B (with CCE) a visible splitting of the transmission dips is observed for coupling to the cladding modes (1ν) with ν = 5,7,9. The splitting and amplitude are seen to increase with higher ν where the core overlap and thus coupling constant increases.

To illustrate the effect of bending, the splitting of the (17)-mode coupling resonances is depicted in Figure 5. The fibres A and B are rotated around its longitudinal axes at steps of $\theta = 45°$ of rotation, and a transmission spectrum are recorded for each value of θ. This series is recorded for 3 different curvatures between 0.15 m^{-1} and 2.2 m^{-1}, where the curvature is defined as $1/r_{curv}$ where r_{curv} is the curvature radius measured in meters. The resonance splitting of the (17)-mode coupling resonance is determined in each spectrum and plotted as a function of θ in the polar graphs in Figures 5a and 5b for the two fibres A and B. The sticker angle θ is the angular component whereas the resonance splitting is the radial component.

In Figure 5a it is seen that the resonance splitting is almost rotation symmetric for the LPG in the fibre with the low CCE (fibre A). The resonance splitting is seen to

expand homogeneously for all directions with increasing curvature. For the 0.15 m^{-1} curvature, the splitting was below the detection limit.

The resonance splitting observed in fibre B is clearly asymmetric in that the splitting is different for different bend directions θ. The largest increase in splitting is observed at $\theta = 0°$. The splitting decreases as θ starts deviating form 0°. The smallest splitting is obtained at $\theta = 180°$. The splitting is almost symmetric for θ's on either side of the axis connecting $\theta = 0°$ and $\theta = 180°$.

Figure 5a and b thus clearly illustrate the effect of CCE on the asymmetry for different bend directions.

The splitting of the coupling resonances is attributed to the breaking of symmetry which perturbs the cladding modes (1ν) thereby introducing a refractive index difference. Since the resonance wavelength for LPG's are very sensitive to changes in effective index even a small refractive index difference results in a large splitting. Using the phase-matching condition:

$$\lambda = \Lambda\left(n_{eff}^{co} - n_{eff}^{cl}\right),$$

For both cladding modes, it is found that the typical splitting of 10 nm corresponds to an effective index difference of 4×10^{-5}, which is a realistic value.

The breaking of symmetry has two main origins:

1) Asymmetries in the fibre geometry, here CCE
2) Bending of the fibre

This is in good agreement with the asymmetric splitting seen for fibre B assuming that the index difference from the two effects add as vectors and the total index difference is the length of the resulting vector, as illustrated in Figure 6.

The resulting splitting calculated as vector addition of the contributions of CCE and bend is shown in Figure 7. The resulting splitting calculated as the length of the resulting vector when the core concentricity error gives an initial splitting on 12 nm in the 0° direction and the bend induced splitting have the values 0, 6, and 12nm. There is a good agreement with the splitting observed in Figure 5.b.

According to the present invention the above-mentioned effect can be used in a fibre-based direction sensitive bend sensor. The fibre with the LPG is aligned so that bending up and down corresponds to 0^0 and 180° respectively. Bends up and down will then respectively increase and decrease the resonance splitting.

It is an advantage that the sensor according to the present invention becomes robust since it uses a difference rather than an absolute wavelength reducing the requirements to the readout system. Since the splitting depends on the effective refractive index difference of different cladding modes and not the difference between the refractive index of the core and cladding mode, the sensor will be less affected by cross sensitivity to temperature, strain, and refractive index.

Since the core concentricity error gives an initial splitting of the resonance the splitting due to bending of the fibre is linear with curvature. This is not the case for the wavelength shift observed by H. Patrick who only observed linear changes for large curvatures since there is no initial perturbation of the fibre.

In summary, the sensor and the method according to the present invention provides a compact, lightweight bend sensor with a good resolution even for small curvatures.

Due to the nature of the sensor, it further provides a convenient way of transporting the output signal from the sensor, namely by transmitting the transmission spectrum to a spectrum analyser by means of optical fibres.

Also, the sensor is a purely optical sensor in that it does not involve any electrical input or output. Since the input and output signal to/from the sensor is an electromagnetic radiation signal, it can easily be transmitted in air over shorter

distances, thereby avoiding the need for mechanical contact in e.g. joints or between movable parts.

In a preferred embodiment, the sensor is adapted to be used to detect motion and stress in structures such as windmill wings, aeroplane wings, concrete constructions, Carbon fibre constructions, glass fibre constructions etc. The sensing fibre can be mounted on a surface of the construction or embedded in the construction.

CLAIMS

1. A direction sensitive bending sensor comprising:

- an optical waveguide structure having a first and a second end and having a first centre axis extending in a longitudinal direction of the optical waveguide structure, said optical waveguide structure comprising, in a cross-section perpendicular to the longitudinal direction, a core and a cladding region,

    - the core region having a second centre axis extending in the longitudinal direction of the optical waveguide structure, said second centre axis being different from the first centre axis, or

    - the cladding region having a second centre axis extending in the longitudinal direction of the optical waveguide structure, said second centre axis being different from the first centre axis,

- means for providing light into the core region at the first end of the optical waveguide structure,

- a grating structure forming part of the optical waveguide structure so as to couple part of a guided mode in the core region to a mode in the cladding region, said grating structure being positioned between the first and second end of the optical waveguide structure, and

- means for determining a parameter associated with a splitted coupling resonance between the core and the cladding modes by detecting light transmitted by the optical waveguide structure.

2. A sensor according to claim 1, wherein the determined parameter relates to a splitting of a resonance coupling in a transmission spectrum.

3. A sensor according to claim 1 or 2, wherein the optical waveguide structure comprises an optical fibre.

4. A sensor according to any of claims 1-3, wherein the cladding region comprises an inner and an outer cladding.

5. A sensor according to any of claims 1-4, wherein the grating structure comprises a long-period grating typically having a period, Λ, within the range 10–5000 μm, preferably in the range 50-1000 μm and even more preferably in the range 100-600 μm.

6. A sensor according to any of claims 1-5, wherein the grating structure forms refractive index modulations in the core region or cladding region or both.

7. A sensor according to any of claims 1-6, wherein the means for providing light into the core region comprises a laser emitting light at essentially a single wavelength.

8. A sensor according to claim 7 further comprising control means for varying the emitted wavelength.

9. A sensor according to any of claims 1-8, wherein the determining means comprises a photosensitive detector capable of detecting the transmitted light.

10. A sensor according to any of claims 1-6, wherein the means for providing light into the core region comprises a light source emitting light at a plurality of wavelengths, such as a light emitting diode.

11. A sensor according to any of claims 1-6, wherein the determining means comprises an optical spectrum analyser for determining a transmission spectrum of the optical waveguide structure.

12. A sensor according to any of claims 1-11, wherein the optical waveguide structure further comprises means for reflecting light transmitted ones by the grating structure back into the grating structure for a second transmission.

13. A sensor according to claim 12, wherein the determining means is positioned so as to detect light emitted from the first end of the waveguide structure.

14. A method for determining an amplitude and a direction of a bend, said method comprising the steps of:

- providing an optical waveguide structure having a first and a second end and having a first centre axis extending in a longitudinal direction of the optical waveguide structure, said optical waveguide structure comprising, in a cross-section perpendicular to the longitudinal direction, a core and a cladding region,

  - the core region having a second centre axis extending in the longitudinal direction of the optical waveguide structure, said second centre axis being different from the first centre axis, or

  - the cladding region having a second centre axis extending in the longitudinal direction of the optical waveguide structure, said second centre axis being different from the first centre axis,

- providing light into the core region at the first end of the optical waveguide structure,

- forming a grating structure in the optical waveguide structure so as to couple part of a guided mode in the core region to a mode in the cladding region, said grating structure being positioned between the first and the second end, and

- determining a parameter associated with a splitted coupling resonance between the core and the cladding modes by detecting light transmitted by the optical waveguide structure, said parameter being uniquely associated with the amplitude and the direction of the bend.

15. A method according to claim 14, wherein the determined parameter relates to a splitting of a resonance coupling in a transmission spectrum.

16. A method according to claim 14 or 15, wherein the optical waveguide structure comprises an optical fibre.

17. A method according to any of claims 14-16, wherein the cladding region comprises an inner and an outer cladding.

18. A method according to any of claims 14-17, wherein the grating structure comprises a long-period grating typically having a period, Λ, within the range 10–5000 μm, preferably in the range 50-1000 μm and even more preferably in the range 100-600 μm.

19. A method according to any of claims 14-18, wherein the grating structure forming refractive index modulations in the core region or cladding region or both.

20. A method according to any of claims 14-19, wherein the means for providing light into the core region comprises a laser emitting light at essentially a single wavelength.

21. A method according to claim 20 further comprising the step of varying the emitted wavelength.

22. A method according to any of claims 14-21, wherein the determining means comprises a photosensitive detector capable of detecting the transmitted light.

23. A method according to any of claims 14-19, wherein the means for providing light into the core region comprises a light source emitting light at a plurality of wavelengths, such as a light emitting diode.

24. A method according to any of claims 14-19, wherein the determining means comprises an optical spectrum analyser for determining a transmission spectrum of the optical waveguide structure.

25. A method according to any of claims 14-24, wherein the optical waveguide structure further comprises means for reflecting light transmitted ones by the grating structure back into the grating structure for a second transmission.

26. A method according to claim 25, wherein the determining means is positioned so as to detect light emitted from the first end of the waveguide structure.

27. A method for determining an amplitude and a direction of a bend in a plane, said method comprising the steps of:

- providing an optical waveguide structure having a first and a second end and having a first centre axis extending in a longitudinal direction of the optical waveguide structure, said optical waveguide structure comprising, in a cross-section perpendicular to the longitudinal direction, a core and a cladding region,

  - the core region having a second centre axis extending in the longitudinal direction of the optical waveguide structure, said second centre axis being different from the first centre axis, or

  - the cladding region having a second centre axis extending in the longitudinal direction of the optical waveguide structure. said second centre axis being different from the first centre axis, and

- providing light into the core region at the first end of the optical waveguide structure,

- bending the optical waveguide structure in the plane and determining a value being associated with a splitted coupling resonance between the core region and the cladding region, said determined value being uniquely associated with the amplitude and the direction of the bend.

28. A method according to claim 27, wherein the deviation between the first and second centre axis, in the cross-section, defines an asymmetry axis, said asymmetry axis being essentially perpendicular to the plane.

29. A method for determining an amplitude and a direction of a bend, said method comprising the steps of:

- providing a sensor, said sensor comprising a first and a second optical waveguide structure each having a first and a second end and each having a first centre axis extending in a longitudinal direction of the optical waveguide structure, each optical waveguide structure comprising, in a cross-section perpendicular to the longitudinal direction, a core and a cladding region,

    - the core region having a second centre axis extending in the longitudinal direction of the optical waveguide structure, said second centre axis being different from the first centre axis, or

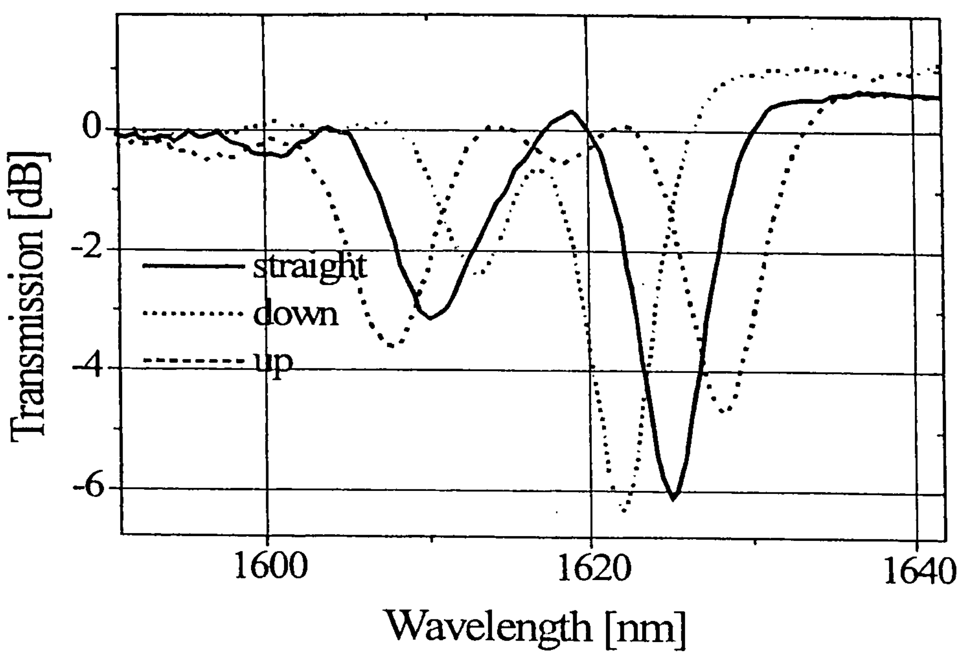
    - the cladding region having a second centre axis extending in the longitudinal direction of the optical waveguide structure, said second centre axis being different from the first centre axis,

    wherein the deviation between the first and second centre axis, in the cross-section, defines a first and a second asymmetry axis for the first and second waveguide structures, respectively, the first asymmetry axis being different from the second asymmetry axis,

- providing light into the core region at the first end of the optical waveguide structure,

- bending the sensor and determining a first and a second value being associated with a first and a second splitted coupling resonance between the core and the cladding region of the first and second waveguide structures, respectively, said determined first and second values being uniquely associated with the amplitude and the direction of the bend.

30. A method according to claim 29, wherein the first asymmetry axis is essentially perpendicular to the second asymmetry axis.



0
-2
-4
-6
Transmission [dB]
straight
down
up
1600
1620
1640
Wavelength [nm]

Figure 1

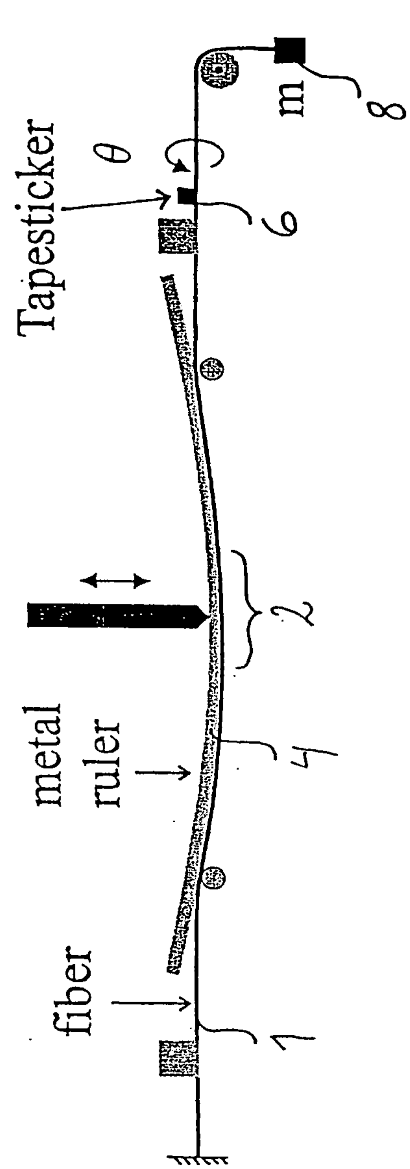


Figure 2

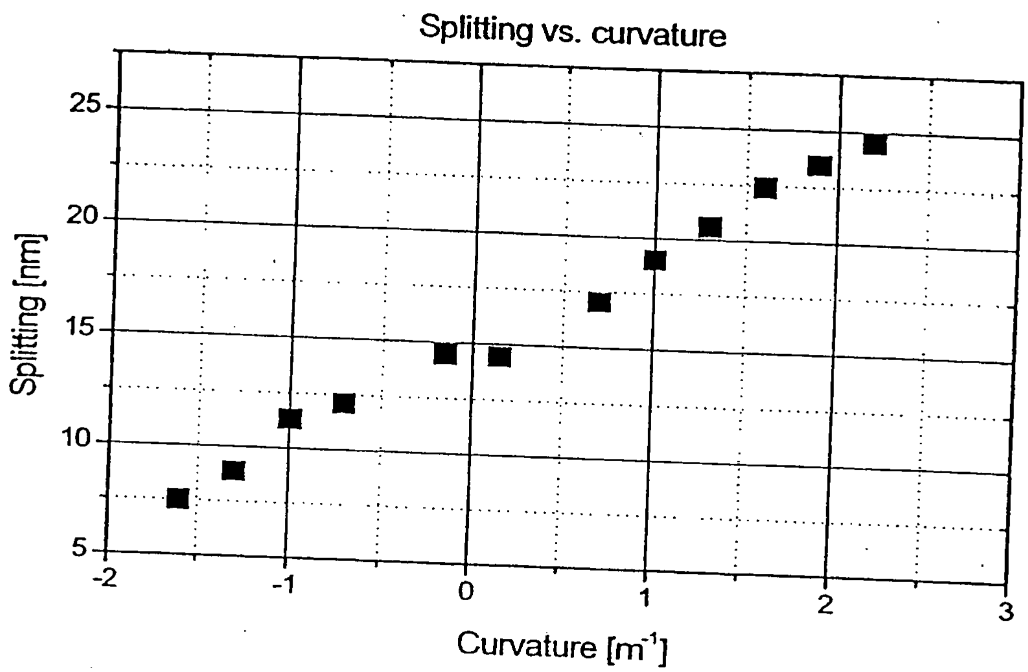
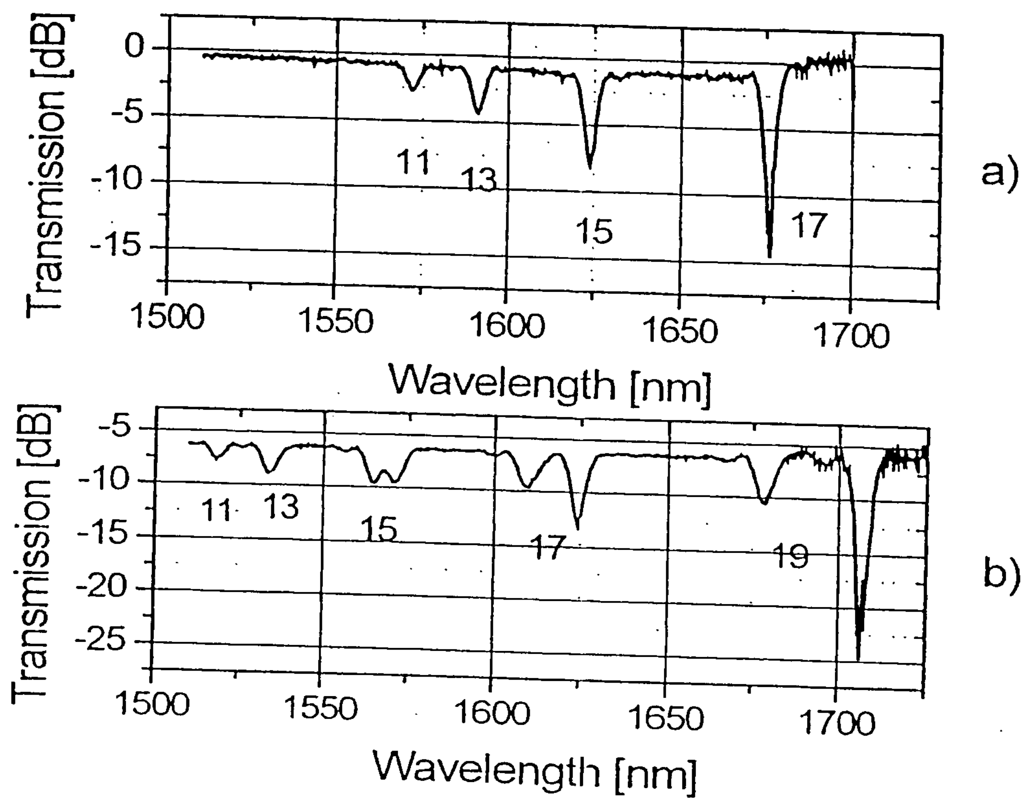

Splitting vs. curvature
Splitting [nm]
25
20
15
10
5
-2
-1
0
1
2
3
Curvature [m-1]

Figure 3



Transmission [dB]
0
-5
-10
-15
11
13
15
17
1500
1550
1600
1650
1700
Wavelength [nm]
a)
Transmission [dB]
-5
-10
-15
-20
-25
11
13
15
17
19
1500
1550
1600
1650
1700
Wavelength [nm]
b)

Figure 4

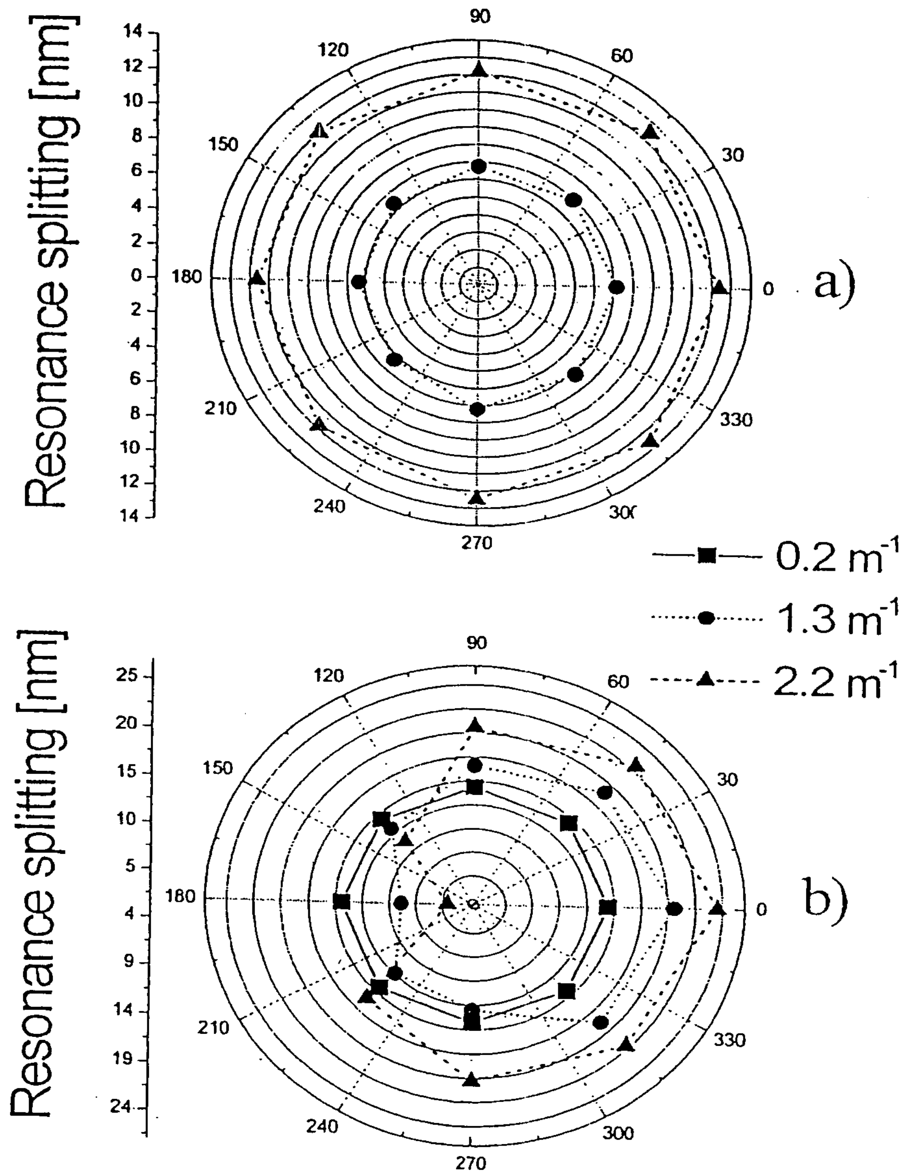

Resonance splitting [nm]
14
12
10
8
6
4
2
0
2
4
6
8
10
12
14
90
120
60
150
30
180
0
210
330
240
300
270
a)
0.2 m-1
1.3 m-1
2.2 m-1
Resonance splitting [nm]
25
20
15
10
5
4
9
14
19
24
90
120
60
150
30
180
0
210
330
240
300
270
b)

Figure 5

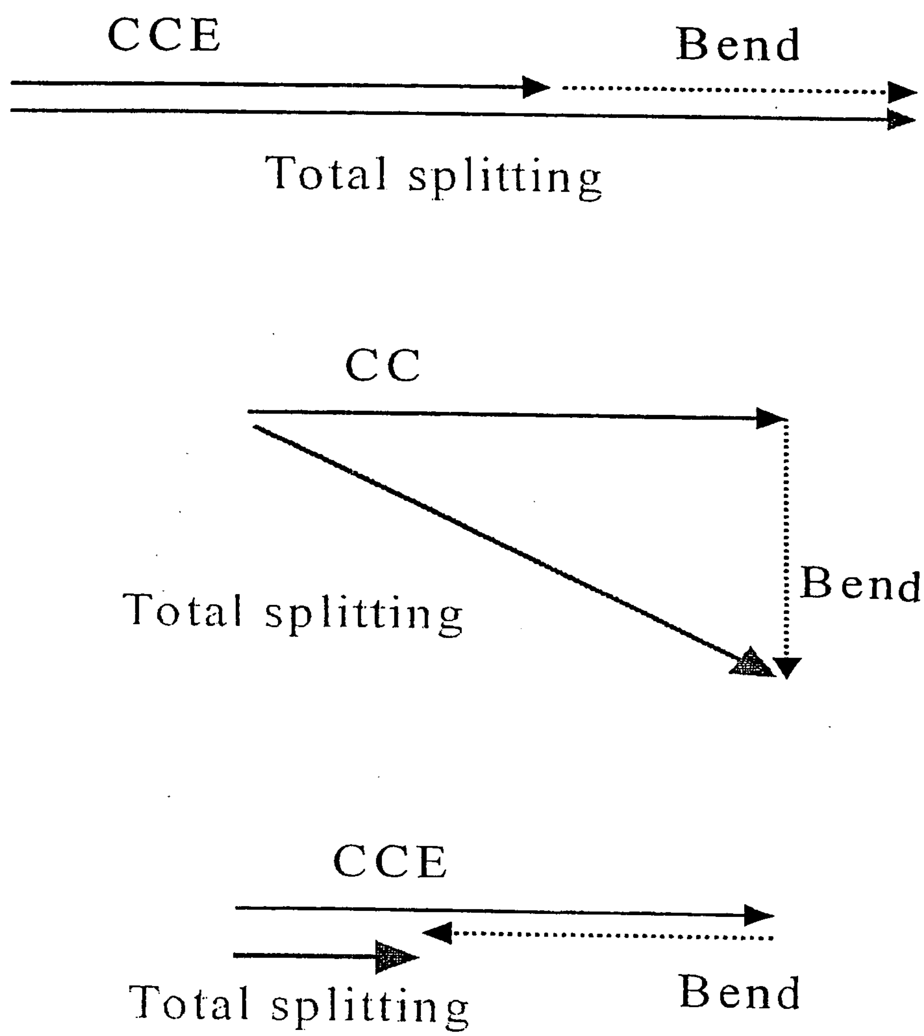

CCE
Bend
Total splitting
CC
Total splitting
Bend
CCE
Total splitting
Bend

Figure 6

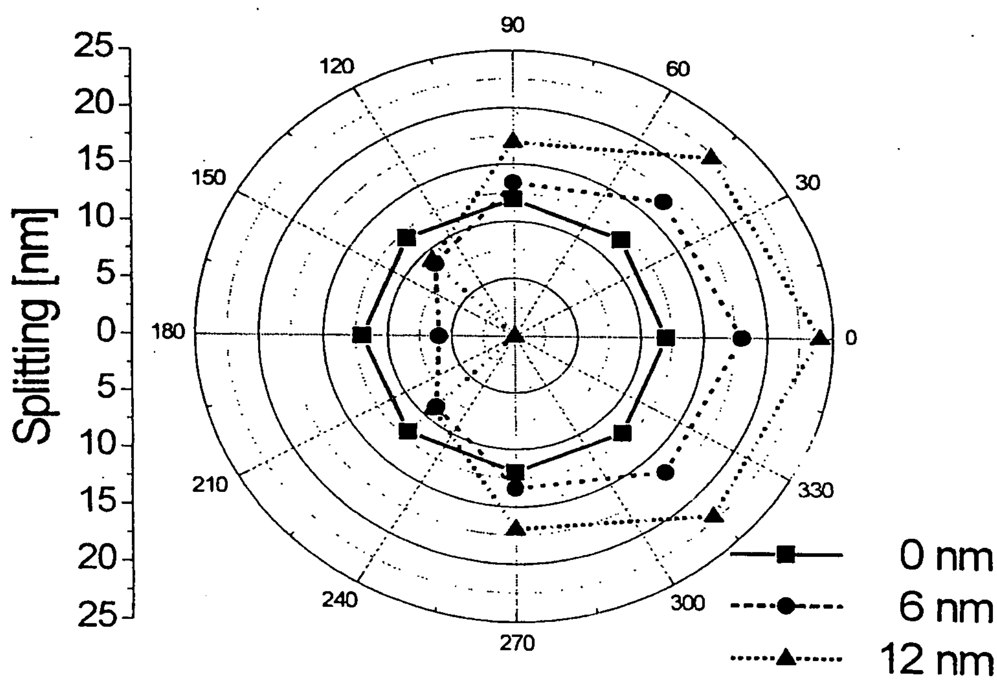

Splitting [nm]
25
20
15
10
5
0
5
10
15
20
25
90
60
30
0
330
300
270
240
210
180
150
120
0 nm
6 nm
12 nm

Figure 7